Performance evaluation of Portuguese constructed wetlands for municipal wastewater treatment

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Abstract: - Constructed wetlands have been used as a technology appropriate for the treatment of municipal or domestic wastewater in some villages in Portugal. Most of constructed wetlands present a low cost (installation and maintenance), low energy requirements and technical skills of operators, environment friendly landscape, and good efficiency and reduced production of sludge. In a situation where is a need of appropriate wastewater treatment from a large number of rural villages, it is appropriate to evaluate the performance of some constructed wetlands systems operate in Portugal, in order to validate them as a credible alternative to conventional methods of wastewater treatment.
This work presents a characterization of twenty constructed wetlands, an analysis of unit costs of treatment and the unit areas, and proceeds to the evaluation of their efficiency on the main wastewaters quality parameters. Moreover, the analysis identifies the major operational problems of these systems, suggesting a few mitigating measures and/or corrective to both the improvement of its operation, and the streamlining of its procedures for an accurate monitoring.

Key-Words: - wastewater treatment; natural systems; constructed wetlands; investment costs, monitoring, performance evaluation.

1 Introduction

The discharge of untreated domestic wastewater in the receiving means creates a negative environmental impact, inversely proportional to its ability to repair due to the high organic load and presence of pathogenic microorganisms in wastewater.
For small communities (less than 2000 inhabitants), it appears that the solutions of biological conventional wastewaters treatment (like activated sludge or trickling filters) have high costs or low efficiencies (like collective septic tanks) that render the fulfilment of more exigent requirements. This has attracted a growing interest for the development and application of low-cost technologies (installation, operation and maintenance) to ensure the sustainability of small wastewater treatment plants (WWTPs).
Natural systems for municipal wastewater treatment, like constructed wetlands (CWs), have been set up all over the world over the last few decades as a good alternative to conventional systems for the sanitation of small communities. Low energy requirements, straightforward operation and maintenance works are some of the most attractive advantages of these technologies.
In most of Mediterranean countries as well as in Portugal there are no specific regulations and design criteria of CWs for wastewater treatment. So, there is a great need to establish regulations suitable for warm climate conditions. [1]. The advantages of CWs application in Portuguese rural communities are unquestionable, because temperature and land availability and costs are not the limiting factors.
The majority of constructed wetlands in Portugal used for the biological treatment of municipal sewage are designed as subsurface horizontal flow (SSHF) systems [2, 3]. At this time, very little data concerning Portuguese CWs performance evaluation had been reported avoiding to confirm its capacity and effectiveness on COD, BOD5, total suspended solids (TSS) and ammonia removal. Data obtained in Spain showed that the average load applied to HF-CW is higher that in otherones cited in the literature and proved that those systems perform very high organic matter removal comparing to the other European countries [4]. This performance could also be achieved in Portuguese CWs due to its close localization, similar climate conditions, regulations and design criteria. However, more data must be

provided in order to validate this conclusion and to establish accurate guidelines for design, management and monitoring procedures, aiming the sustainability of those wastewater treatment facilities.
The main objective of this work is to contribute to increase the knowledge about the Portuguese constructed wetlands characteristics and performance, in order to validate it as a credible and suitable alternative for wastewater treatment in rural areas [5].
This work presents a synthesis of data obtained through an extensive survey performed in twenty Portuguese constructed wetlands utilities. Based on this information, some design parameters and removal pollutant efficiencies were calculated. Besides identifying the main operational problems observed, it was also possible to detect inadequate monitoring procedures, aiming, with some proposed corrections, to improve the performance of these low-cost wastewater treatment utilities.

2 Methods

2.1 Constructed wetlands composition

The constructed wetlands can have various forms or configurations, depending on the need to adapt to the morphology of the land, but usually have rectangular form.
In general, the wastewater facilities using constructed wetlands are also composed by several unit processes performing preliminary, primary and secondary (biological) treatments.
The preliminary treatment is generally composed of a grid to remove the larger suspended solids.
The primary treatment is provided by a settling and flotation tank (*Imhof* tank or septic tank), with efficiencies from 30 to 50% in TSS removal and near 20% in organic matter (DBO) removal, including oil and fats. This body, and reduce, by simple processes of separation, the concentration of some pollutants and contaminants to avoid clogging the sub-surface of the bed, thereby increasing its operation period [6].
The biological treatment is provided by one or more beds of macrophytes (Fig. 1). The media bed is essential for plants (macrophytes) anchorage and biofilm (aerobic and anaerobic bacteria) development, which is crucial to performs the biodegradation of organic matter. The continuous growth of roots, adsorption, sedimentation and precipitation of wastewater compounds and, also, the biofilm release over operation time leads to the development of clogging, worsening the solute distribution and the overall performance of the system.

Fig.1 Macrophytes beds construction

The filling of the bed consists of several layers with different size and height, to minimize the risk of clogging [7]. The bed is usually sealed at the bottom and slopes with a screen of polyethylene to prevent contamination of groundwater and to allow that macrophytes are continuously fed with organic matter.
Several species of macrophytes have been used for municipal wastewater treatment, but the most frequent are *Typhas*, *Phragmites*, *Juncus*, *Scirpus* and *Iris* (Fig. 2).

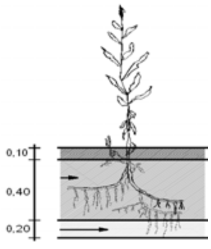
Family: *Iridaceae*
Specie: *Irís Pseudacor*u

Family: *Juncaceae*
Specie: *Juncus effusus*

Family: *Gramineae*
Specie: *Phragmites australis*

Family*: Cyperaceae*
Specie: *Schoenoplectus lacustris:*

Family: *Typhaceae*
Specie: *Typha latifolia*



Schematic bed composition

Fig.2 Major Species of macrophytes used for municipal wastewater treatment

These plants are adapted to live in waters with high organic load and, through photosynthesis, send oxygen to the roots promoting the degradation of organic matter, through the living organisms associated with its root system.

2.2 Classification of constructed wetlands

The classification of constructed wetlands is based on the specie of plant used (floating, submerged or emerging). For the other hand, the emerging bed plants can also be classified according to the type of flow (surface or sub-surface).

The beds with sub-surface flow may be classified according to the direction of flow: horizontal, vertical, or hybrid [8].

In a rhizospheric system (Fig. 3), corresponding to an aquatic macrophytes emerging system with a sub-surface flow, wastewater is distributed into the bed over the area of roots and rhizomes.

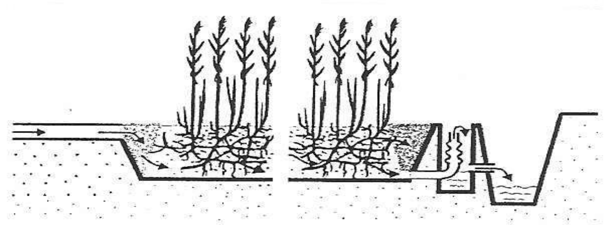


Fig.3 Rhizospheric system scheme

During its percolation several physical, chemical and biological processes contribute to a good depurative performance, achieving, in most cases, the legal limits for wastewater discharge stated in the European emission standards.

The constructed wetlands with sub-surface flow derive advantage of percolation through a stratified medium, where the mechanism of biological filtration shows higher rates of removal of pollutants and contaminants when compared to surface flow systems, thereby requiring a smaller area of occupation. Moreover, the fact that the water level is below the surface, besides being an aesthetic advantage of the bed, favours the stability of biochemical reactions in the lower layers, even in cooler climates, due to the action of the soil as insulating heat.

2.3 Constructed wetlands design methods and operating conditions

All of the most widespread CW design methods, except the EPA method [9], calculate the surface area of the beds as a function of the organic matter decay based on a first order kinetic equation. The difference found in the several CW design methods searched lies in the values used for the kinetic constant and in its variation with temperature of the medium. Despite its specificity (areas of operation to separate), the model proposed by the EPA based on the size of the beds, has the basic elements common to other methods, including flow rate, the concentrations of the most relevant parameters (BOD5, COD, TSS, N or P) and the removal rates required for this parameters.

Operating conditions of a CW for an affective area can be described by the range of values observed for the several major hydraulic and quality parameters: flow rate; hydraulic loading; hydraulic retention time; BOD5, COD and TSS influent concentrations; and organic matter loading.

In general, it can be said that the biological processes provide elements to calculate the surface area of the bed, the characteristics of the used macrophytes determine the bed' depth, and the hydraulic parameters (flow rate, hydraulic retention time, head loss) determine the volume and the configuration of each bed.

2.4 Portuguese constructed wetland survey

The need to select appropriate and sustainable solutions for a large number of rural Portuguese villages, where WWTPs must be designed and built (in a short term), became relevant to evaluate the performance of the existing constructed wetlands and the identification of its major operational problems.

With this goal, twenty SSHF_CW systems were selected to study their characteristics and operations conditions, across almost all the country. The survey was intended to be as comprehensive as possible through consultation with experts and utilities' managers, and to guarantee the representativeness of the sample, considering different climatic zones, cultural habits, type of settlement and economic activities.

Wastewater treatment facilities selected are operating since late 90s, and were designed for a served population between 109 and 1160 persons equivalent (PE). Most systems have a septic tank as the primary treatment.

Table 1 presents a summary of the information obtained through on-site visits, namely the type of system, surface, years in service, efficiency, costs, flow rate, type of macrophytes, operational problems, type of media, influent and effluent contaminant concentrations, plant configuration and primary treatment. Furthermore, a questionnaire was send to the administrations also asked for the main physico-chemical parameters analysed at each facility.

It appears that only part of these systems has been carried out regular monitoring of the major wastewater quality parameters (BOD5, COD, TSS, P and N), before and after treatment procedure. Some wastewater utilities only control the emission values (in the effluent) to assess its compliance with discharge legal limits.

Table 1 Summary of characterization of the Portuguese constructed wetlands surveyed.

	Year of service	P.E.	Surface (m^2)	Surface of beds (m^2)	Macrophyte specie	Beds number	Cost (€)	Frequency analysis	Maintenance	Problems
Alcochete	2001	500	4000	1764	*Phragmites*	4	189500	Semester	Yes	No
Aranhas	2004	437	4100	836	*Phragmites*	1	…….	Monthly	Yes	Clogging, Solids
Arganil	2002	109	800	160	*Junco*	1	41000	Annual	No	Clogging, Solids
Carregal do Sal	1998	200	655	338	*Phragmites*	2	--------	Quarterly	Yes	Clogging
Condeixa	2002	600	4600	1600	*Lírio, Typha*	1	144500	Quarterly	Yes	Clogging
Covilhã	1999	840	2398	1045	*Typha*	1	99760	…….	No	Clogging, Solids
Grândola	2000	500	1100	500	*Phragmites*	1	82182	…….	No	Clogging
Guarda	1999	1160	2500	2500	*Phragmites*	2	130000	Monthly	Yes	Clogging, Odors
Madeira	2003	200	541	441	*Phragmites, lírio e junco*	3	130000	Monthly	Yes	No
Mealhada	2000	125	1000	350	*Phragmites*	1	38513	Monthly	Yes	Clogging
Odemira	2001	350	1360	714	*Phragmites*	2	87040	Annual	Yes	No
Penacova	2001	500	3240	1860	*Phragmites*	2	97266	Quarterly	Yes	Clogging
Rossas	2001	600	1800	1444	*Phragmites*	4	100802	Monthly	Yes	No
Salamonde 1	1999	250	700	289	*Phragmites*	2	64750	Monthly	Yes	No
Salamonde 2	2001	250	600	289	*Phragmites*	2	--------	Monthly	Yes	No
Salvador	2004	563	3100	630	*Phragmites*	2	…….	Monthly	Yes	Clogging, Solids
St.Comba Dão	1999	300	1153	585	*Typha*	1	31159	Annual	No	Clogging, Solids, Odors
Tondela 1	1997	200	686	656	*Junco*	1	--------	Annual	No	Clogging
Tondela 2	1998	200	562	532	*Junco*	1	--------	Annual	Yes	Clogging
Vila de Rei	2000	1054	4325	855	*Phragmites*	1	185000	Quarterly	yes	Clogging, Odors

Moreover, not all WWTP managers provided other relevant information requested, like the cost of the system, the design criteria adopted, and the maintenance tasks usually performed.

3 RESULTS

Based on data obtained in the characterization of the constructed wetlands surveyed, it was performed a detailed analysis of the areas occupied by the various systems and their macrophytes beds, as well as the costs associated with its implementation.

Related to specific surfaces and specific investment costs, the following five design parameters were calculated to allow a better comparison between the surveyed CW:

(1) Total area of the WWTP *per capita*;
(2) Beds area *per capita*
(3) Investment cost of the WWTP perr unit area
(4) Investment cost of the beds per unit area;
(5) Investment Cost per person served.

Table 2 presents a summary of the reference values obtained for each of these five specific parameters.

The average cost of investment is around 246 euros per capita.

The large variation in values obtained for the CW investment cost per unit area (between 27 and 294 euro) could be explained by the fact that some systems (lower values) have been designed and constructed by the municipalities (except the system of Madeira Island), unlike those who were executed by companies of specialty pages, which present the highest cost values.

The average area of the systems is about 4.4 m^2, while the average area of the bed per person served is about 1.9 m^2.

There is also noted that the use of smaller areas *per capita* does not necessary imply an inferior performance of the systems as we can see in the cases of Vila de Rei and Alcochete WWTPs, respectively.

Table 2 Reference values of specific areas and investment unit costs.

WWTP	Specific surfaces		Specific investment costs		
	System (1)	Beds (2)	Cost/ m^2 (3)	Cost/ m^2 of bed (4)	Cost/ inhab. (5)
	m^2/inhab	m^2/inhab	euro	euro	euro
Madeira	2.7	1.5	294	442	650
Alcochete	8.0	3.5	47	107	379
Aranhas	9.4	1.9	-	-	-
Condeixa	7.7	2.7	37	90	285
Penacova	5.4	3.1	30	52	162
Rossas	3.0	2.4	56	70	168
Salamonde 2	2.4	1.2	-	-	-
Salvador	5.5	1.1	-	-	-
Vila de Rei	4.1	0.8	43	216	176
Arganil	7.3	1.5	51	256	376
Carregal do Sal	3.3	1.7	-	-	-
Covilhã	2.9	1.2	41	95	119
Grândola	2.2	1.0	75	164	164
Guarda	2.2	2.2	52	52	43
Mealhada	8.0	2.8	39	110	308
Odemira	3.9	2.0	64	121	249
Salamonde 1	2.8	1.2	72	224	259
St. Comba Dão	3.8	2.0	27	53	103
Tondela 1	3.4	3.3	-	-	-
Tondela 2	2.8	2.7	-	-	-
Average	**4.4**	**1.9**	**49**	**119**	**202**
Standard deviation	2.4	0.9	14	70	110

The operational and maintenance costs were not examined in this study for lack of consistent information, but based on references in the literature they are usually higher in the conventional systems, due to the need of more technical expertise, energy consumption and frequent maintenance requirement of electromechanical components.

The energy costs associated to CW systems and gravitational flow is relatively low when compared with those of conventional systems. It is a solution with high energy efficiency especially for populations less than 500 inhabitants [10].

The performance evaluation of CW was carried out only in half of the systems studied, due to the inconsistency of some data. This analysis was focused primarily on the analysis of whether the average removal efficiencies of parameters BOD5, COD, TSS, P and N, based on the values collected in the survey related to the parameters concentrations in the influent and effluent (Table 3).

The results here presented confirm the good performance of these systems in the removal of BOD5 and COD, in terms of average values, and a very good performance in the removal of TSS. However, they should not be used when the effluent is discharged to sensitive receiving waters, for not increase their eutrophication vulnerability associated to high concentrations of nutrients.

Based on the results analysis, it appears that [10]:

- Mean values of BOD5 discharge comply in all situations the Portuguese Law-Decree 152/97, but the same is not happening for the Portuguese Law-Decree 236/98 (three situations occurred in which the average is above the legal limit);
- Mean values of discharge of COD are not met in two cases, by reference to any of the both Law-Decrees (LD);
- All systems meet the legal requirements for TSS;
- In relation to phosphorus, the values advocated by LD 236/98 are always met, but this did not happen in relation to the values of LD. 152/97;
- The average emission of nitrogen does not meet the legal limits.

Table 3 Average concentrations and efficiencies of BOD5, COD, TSS, P and N removal.

WWTP	**BOD$_5$** (mg O_2/L)			**COD** (mg O_2/ L)			**TSS** (mg/L)			**P** (mg/L)			**N** (mg/L)		
	Aflu.	**Eflu.**	**Efic (%)**	**Aflu.**	**Eflu.**	**Efic (%)**	**Aflu.**	**Eflu.**	**Efic %**	**Aflu.**	**Eflu.**	**Efic %**	**Aflu.**	**Eflu.**	**Efic %**
Madeira	171	9	93	329	27	77	287	17	81	-	-	-	-	-	-
Alcochete	97	33	70	1009	318	66	62	23	55	3	2	27	61	34	50
Aranhas	298	35	78	610	107	76	570	21	80	6	3	38	80	31	56
Condeixa	159	22	75	409	78	65	316	21	81	11	6	38	132	47	48
Guarda	403	44	84	880	131	77	408	27	79	8	5	31	107	33	61
Penacova	554	42	89	937	123	82	290	22	84	12	7	30	78	48	34
Rossas	516	15	95	1076	58	91	631	9	97	17	1	95	120	31	72
Salamonde	267	24	85	474	77	81	257	20	91	11	3	66	97	33	61
Salvador	524	62	83	889	170	80	366	31	82	8	5	33	125	45	61
Vila de Rei	251	37	86	618	133	68	238	20	88	-		-	-	-	-
Average	**324**	**32**	**84**	**723**	**122**	**76**	**343**	**21**	**82**	**10**	**4**	**45**	**100**	**38**	**55**

The CW utilities' managers had pointed the following main operational problems:

• Clogging of the beds, which is reflected in its surface flooding resulting in loss of efficiency of treatment as the pores of the bed no longer be free to allow percolation of the effluent to be treated;

• Absence of a monitoring plan adequate to control the quality of treated effluent at the various stages of the treatment process;

• Deficiencies in the development of macrophytes planted, giving a growth rate higher than the top of the bed, which favours predominantly occupying the rest of the bed by invasive species;

• Illegal discharges of industrial wastewaters into public network sewage, which changes considerably the characteristics of the inflow wastewater of CW systems.

This survey showed that only 30% of the selected systems did not present problems of operation. Furthermore, almost 25% of the CW systems have no maintenance and 70% had experienced clogging of its macrophytes beds. About 25% of the systems allowed the passage of solids to the constructed wetland and 15% showed the production of undesirable odours.

4 Conclusions

This work presents the results of performance evaluation of twenty Portuguese SSHF-CW systems. The mean removal efficiencies of pollutants were high for BOD5, COD and TSS, and, in most cases, the effluent quality was in compliance with the ELVs defined in Portuguese standards. The same does not occurred with the emission values of nutrients, preventing its use in receiving waters bodies subjected to eutrophication processes.

The survey carried out of the main problems associated with the operation of the systems studied showed that only 30% of systems had been operating without any problems, giving the remaining problems of clogging of the beds, identified as the main problem of this kind of wastewater treatment system. This is directly linked to the high percentage of systems without an accurate monitoring program for the quality control of treatment processes, focusing only on compliance with the standards of discharge and, for economic reasons, only analyzes the treated effluent. It is also neglected the issues related with the hydraulic behaviour of CW, like the head loss control and design parameters measurements (like flow rate, retention time and hydraulic loading).

The results obtained in this work encourage the development of future studies to increase the performance of these wastewater systems based on a better knowledge of the influence of hydraulic conditions in the pollutants removal efficiencies.

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